Journal of the British Interplanetary Society, Vol. 36, pp. 231-238, 1983.

ORBITAL RING SYSTEMS AND JACOB'S LADDERS — III

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A method for transferring payloads into space without using rockets has been presented in Part I, in which massive rings encircle the globe in a low orbit supporting stationary 'sky-hooks,' from which cables hang down to any point on the Earth's surface. Vehicles can climb up these 'ladders' into orbit, or can accelerate along the rings. The structure, deployment and use of such Orbital Ring Systems was examined in Part II. Further applications are now considered, including several methods for obtaining power from space. The future potential of Orbital Ring Systems for very large-scale construction projects and applications is noted.

1. INTRODUCTION

The origins of the concept of Space Elevators lie far back in time. In Genesis 28 v 12 Jacob dreamed of a ladder set up on the Earth, the top of which reached to heaven. Earlier still, the inhabitants of the city of Babel are reported to have attempted to build "a tower with its top in the heavens" (Genesis 11 v 4). In more recent literature the story of Jack and the Beanstalk is well known. Each of these early dreams or fancies have helped provide names for workers in this field today: Jacob's Ladders, Orbital Towers, Beanstalks and others.

The modern concepts made use of the fact that a body some 36,000 km above the equator revolves about the Earth at the same rate as the Earth rotates, thereby hanging apparently motionless in the sky. A long cable, dangling from geosynchronous orbit, could be supported by a counterweight suspended further out; the Earth's rotation would keep the cable taut and permit its use as support for a Space Elevator. Unfortunately, a cable capable of supporting thousands of kilometres of its own length is not yet practicable.

To avoid the requirement for ultra-strong materials I have devised another system, in which the supporting element is a massive ring in Low Earth Orbit, as illustrated in Fig. 1. Here the comparatively short cable from the ring to the ground (called a Jacob's Ladder) is suspended from a 'Sky Hook' which rides upon the ring, supported by magnetic levitation. The skyhooks and ladders are geostationary, but the orbital ring is moving at slightly more than orbital velocity. The complete 'Orbital Ring System' (ORS) appears to be within reach of present-day technology.

Part I of this study [1] was devoted to the theoretical aspects of Orbital Ring Systems and Jacob's Ladders, the initial concept being generalised to include Eccentric Orbital Ring Systems (EORS) and Partial Orbital Ring Systems (PORS); a large family of configurations was shown to exist.

Part II [2] was concerned with various aspects of engineering, logistics and safety, describing how Orbital Ring Systems could be built in the near future and put to use in transporting cargoes into space; costs and potential economic returns were also considered.

In Part III (this paper) I shall be dealing with additional aspects of the construction and use of the Orbital Ring Systems, building upon the theoretical foundation of Part I and the work in Part II. In particular, I shall be considering the problem of providing power from space. I shall conclude by pointing out how the ORS concept can be applied to certain extremely ambitious projects involving astro-engineering on the grandest scale. I hope to convince you that the potential for human growth and achievement has never been greater.

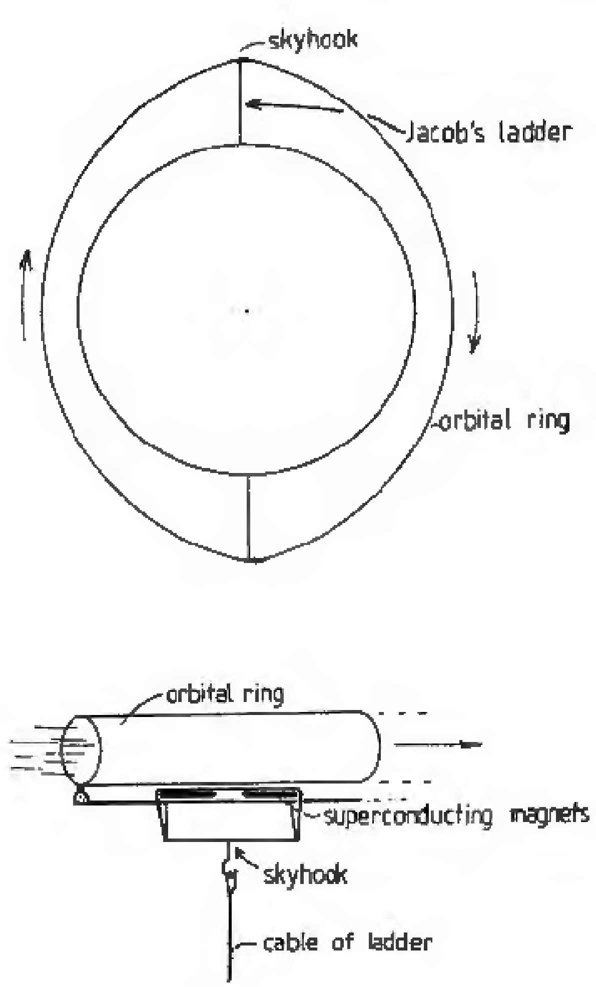

Fig. 1. The Orbital Ring System.

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2. POWER FROM SPACE WITH ORBITAL RING SYSTEMS

2.1 Solar Power from High or Geosynchronous Orbit

Solar Power Satellites (SPS) are best located in high orbits where they are rarely eclipsed. The available insolation is high and constant, and there are no fuel costs, so power can be produced very cheaply (once the power satellite has been built). However, to be useful on Earth this power must be brought down to ground level.

Usually, the method considered involves power transmission by a beam of microwaves from the SPS, the power being recovered by 'rectennas' on Earth. It is likely that this process would be around 50% efficient (DC on SPS to AC on Earth transmission lines).

There are several imperfections in this scheme. Each SPS must be flown in equatorial geosynchronous orbit, potentially causing interference to certain radio services and to radio astronomy. The power beam could easily be directed to wherever the power is required, but unfortunately the rectennas would take up quite a lot of ground area. Some concern has also been expressed that such high power microwave beams might have deleterious effects on the upper atmosphere (although recent tests have demonstrated that considerably more than the nominal 23 mW/cm^2 can be passed safely); there have also been the usual ridiculously exaggerated fears of low level exposure of the general public to microwaves. These problems can all be overcome (except, of course, for the fundamentally irrational objections of those groups that are automatically opposed to all new technology) but one can see that there could be economic and other benefits in avoiding them.

Here we may mention that Orbital Ring Systems are not likely to have any deleterious effects upon radio astronomy or communications. An ORS will not in itself be an active source of radio frequency interference (RFI) and although it will reflect back any RFI generated on the Earth's surface the reflected noise will be weak (some 60db down on direct RFI, since the ORS will cover only about a millionth of the sky). The effects for even single-dish radio-astronomy would be small, less than the typical effect of passing aeroplanes. It should also be pointed out that, once an SMF is available, it will be scientifically and economically advantageous to build any new telescopes in space.

An alternative scheme for bringing down the power makes use of the EORS up to the satellite orbit (Fig. 2). Each SPS generates electrical power which is used to drive linear induction motors or mass-drivers against the High Earth Orbital Ring System (HEORS). The rings of the HEORS are thus spun up in opposite directions; there is no net force on the SPS. As the rings pass through Power Transfer System One (PTS 1) they are slowed back down again, and the regenerated power is used to speed up the EORS passing the same point. In LEO the EORS is slowed down by PTS 2, and the Low Earth Orbital Ring Systems (LEORS) is speeded up. Finally, skyhooks recover power from the LEORS and send it down ladders to the ground, where is can be used to electrolyse water or to feed the electricity grid.

Imagine a twin-ring system with orbital velocity V_g (Fig. 3). There is a 'centrifugal force' acting, with the acceleration due to gravity, to maintain the orbit; the force per unit length

$$f = m_g V_g^2 / r_c \tag{1}$$

where r_c is the radius of curvature and m_g the total line density.

If the rings approach S with velocity (V_g-V), line density m_-, and are accelerated to V_g+V), line density m_+, we now have (Fig. 3b)

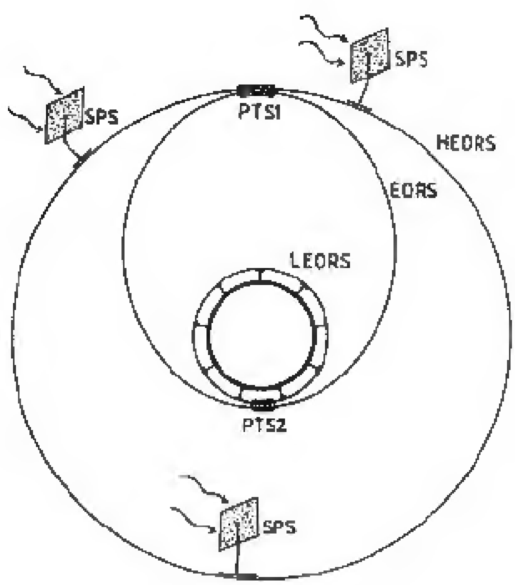

Fig. 2. Power Transfer *via* Orbital Ring Systems.

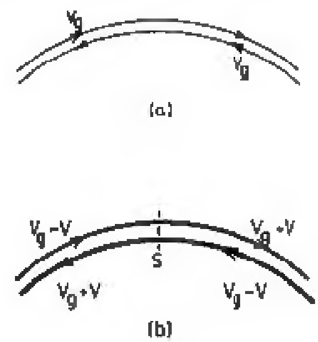

Fig. 3. Orbital Rings being accelerated at a PTS.

$$f = ((V_g - V)^2 m_- + (V_g + V)^2 m_+)/2r_c \tag{2}$$

But m is inversely proportional to orbital speed, so

$$f = ((V_g - V) m_g V_g + (V_g + V)/2r_c = m_g V_g^2 / r_c \tag{3}$$

Since this is the same as Eq. (1) the pair of rings will still follow the original orbit, provided that suitable vertical forces between the rings are used to hold them together.

The power input at S is calculated from the difference in kinetic energies per unit time:

$$P = \tfrac{1}{2} m_+ (V_g + V)^3 - \tfrac{1}{2} m_- (V_g - V)^3 \tag{4}$$

Substituting for m_+ and m_- we have

$$P = \tfrac{1}{2} m_g V_g (V_g + V)^2 - \tfrac{1}{2} m_g V_g (V_g - V)^2 \tag{5}$$

$$\therefore \quad P = 2 m_g V_g^2 V \tag{6}$$

The power carrying capacity of the arrangement in Fig. 2 is worked out in Table 1. In order to cope with projected SPS production we would need to be able to transport about 10^{13} W.

TABLE 1. ORSs for Power Transport.

Units	r_{ap} (1)	r_{pe} (1)	V_{ap}	$P/m_{ap}V$ (2)	P/MV	M/m_{ap} (3)	V/V_{ap}	M/P	fv (4)
	Mm	Mm	kms^{-1}	$MJ\ kg^{-1}$	$J\ kg^{-1}\ m^{-1}$	10^6	-	$kg\ kW^{-1}$	-
EORS (5)	42.4	6.7	1.61	5.2	0.085	61.3	0.5 0.3	14.7 24.5	12.7 9.7
HEORS (5)	42.4	42.4	3.08	19.0	0.071	266	0.5 0.3	9.1 15.2	4 1.9
LEORS (5)	6.7	6.7	7.75	120	2.85	42.1	0.5 0.3	0.09 0.15	4 1.9

Notes: (1) Apogee and perigee radii in 1000 km; (2) From Eq. (6); (3) From Eq. (88) of Part I; (4) $f_v \equiv V_{max}/V_{min}$; (5) See Fig. 2.

Let the LEORS have the same mass as the HEORS (so that there is a reservoir containing about a week's supply of energy) and use the smaller value of f_v from the table for the EORS. Then,

$$\text{Total Mass of Power Transport Rings} = 4.3 \times 10^{11}\,\text{kg} \quad (7)$$

The line density of these rings is similar to that of the main ORS in Section 3. 5 of Part II so the same specific cost can be used (25 m\$ kg^{-1})

$$\therefore\ \underline{\text{Cost of Power Transport Rings} = 11\ \text{G\$}} \quad (8)$$

I have suggested that the acceleration and deceleration of the rings might be carried out by means of linear induction motors. However, a scheme using a version of the 'mass-driver' [4] could prove more efficient.

Each 'unit cell' of a ring can have its own superconducting coil (corresponding to the bucket coils of the mass-driver); the drive coils would be on the PTS. In the decelerating sections the mass-driver has its phasing arranged in reverse; energy is dumped into the coil and capacitor and fed into the appropriate drive coil of the accelerating section.

If design parameters similar to tose of Ref. 4 are used (with the necessary changes of geometry) we can expect the superconducting coils to mass about 1 kg m^{-1} at apogee, or 3×10^8 kg in all. Judging by the Table on page 125 of NASA SP-428 [3] the mass of each PTS will be about 3 kgkW^{-1}, or some 1×10^{11} kg in all (including PTS 1, PTS 2 and the mass-drivers at each SPS and ladder). The 'Kinetic Power Mass' is of course the SPS itself and is about 5 kgkW^{-1}, that is 5×10^{10} kg for the full 10^{13} W. There remains only the mass of the (probably) superconducting cable down the ladders; here a high line voltage should be used (500 kV would mean 1×10^8 kg of superconducting cable).

As a rough estimate, then, we can say

$$\text{Cost of superconductors for Power Transport} = 1\ \text{G\$} \quad (9)$$

$$\text{Cost of PTSs and drivers for Power Transport} = 100\ \text{G\$} \quad (10)$$

The important distinction between these two is that Eq. (9) must be paid at once, like Eq. (10): but each PTS can be made much smaller initially and extra portions can be added as more SPSs come on-line.

The rings going through PTS 1 will be accelerating at approximately 10 ms^{-2} and the completed driver will be some 300 km long.

The efficiency of each stage of acceleration and deceleration will be about 97% (Ref. 3 p. 125), so the overall efficiency (SPS to ground) will be about 80%, which compares favourably with the efficiency of the Amplitron-rectenna link (up to 70%). There will also be a fixed cryostat power requirement of up to 100 GW (probably $\sim$ 10 GW).

It is likely that this system for power transport would require a similar amount of labour as the setting up of phased arrays of Amplitrons or Klystrons; the cost would probably be somewhat less, since Amplitrons use precisely machined samarium-cobalt magnets whereas mass-drivers use mostly cheaper materials like aluminium. By the time that 10^{13} W was on-line the specific cost of the whole system, including the SPSs, would be down to about 20 \$$kW^{-1}$ (one tenth the cost of conventional fossil fuel or fission power plant); running costs would probably be around 1 \$/kWyr so that the cost of electricity at the foot of the ladders could fall as low as 0.2 m\$/kWhr for the power company or electrolysis plant. Of course, the cost to the consumer would be rather higher, because of the cost of distribution, maintaining transformers, transmission lines, etc. Nevertheless, liquid hydrogen could be made available at a competitive price (around 5 c\$ kg^{-1}) as a fuel for cars and machinery.

The massive rings of the system could also be useful for transporting payloads to high Earth orbit and beyond, as well as providing a link with the Power Satellites themselves, with manufacturing facilities and perhaps the habitats.

Obviously it is not necessary to bring all the power down a single EORS. If a number of independent EORs and PTSs are built the redundancy improves the reliability of the system; an accident to one ring will not prevent the power from getting down to Earth. Moreover, other geometries and combinations of precessing and non-precessing rings are possible; and the location of the SPSs is not fixed — they need not be in a geosynchronous orbit.

A Power Transport Ring System (PTRS) is therefore an economically viable alternative to the use of microwaves for bringing power from Space down to Earth.

2. 2 Power from Gravitational Energy

Because of the Earth's gravitational attraction any body orbiting about it has both kinetic and potential energy; if the body were to be slowed and brought down to the ground by a mass-driver, say, its energy could be extracted and put to use. The Moon is just such a body, a great store of energy ($\sim 4 \times 10^{30}$ J). Soil could be mined on the Moon, sent up ladders to LLO, from LLO to LEO by ORS, and then down ladders to the Earth. As it fell from Moon to Earth the lunar soil would gain kinetic energy, which could be recovered at the ORS in LEO. A constant stream of mass from the Moon would provide continuous power to the rings of a LEORS upon passing a PTS in LEO (Fig. 4).

Consider a mass flow from Moon to Earth of $\dot{M}_{me}$ and

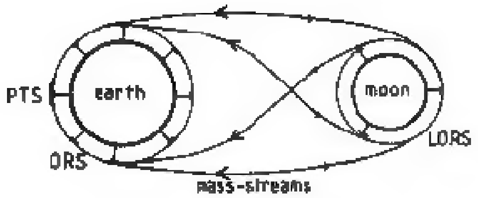

Fig. 4. Mass-flows between Earth and Moon.

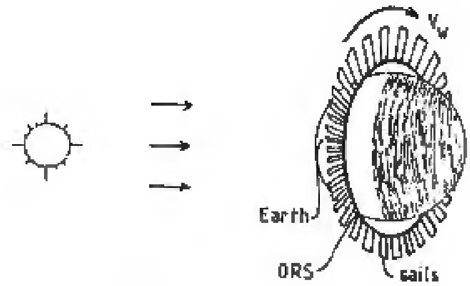

Fig. 5. An Earth Orbit Light-sail Windmill.

from Earth to Moon of $\dot{M}_{em}$. Let the effective escape velocity of the Moon be V_m and of the Earth V_e (including a correction for the relative orbital velocities); and let the Earth-Moon mass-stream have a velocity at infinity of V_∞.

Then, the power flow at the Moon is

$$P_m = \tfrac{1}{2} \dot{M}_{me} V_m^2 \tag{11}$$

supplied as kinetic energy of the mass-stream from Earth:

$$P_m = \tfrac{1}{2} \dot{M}_{em} (V_m^2 + V_\infty^2) \tag{12}$$

The power required for this at Earth is

$$P_e = \tfrac{1}{2} \dot{M}_{em} (V_e^2 + V_\infty^2) \tag{13}$$

and the net power output at Earth is

$$P_o = \tfrac{1}{2} \dot{M}_{me} V_e^2 - P_e \tag{14}$$

The net mass flow is

$$\dot{M}_o = \dot{M}_{me} - \dot{M}_{em} \tag{15}$$

Hence

$$P_o = \tfrac{1}{2} \dot{M}_o (V_e^2 - V_m^2) \tag{16}$$

For a given net flow the values of $\dot{M}_{me}$ and $\dot{M}_{em}$ are minimised when $V_\infty \gg V_m$.

For the Earth-Moon system the specific energy $\simeq 60$ MJ kg^{-1}. Allowing for losses and inefficiencies, one would obtain about 15 kWhr per kilogram of mass transferred to the Earth.

To provide for 10^{13} W the mass flow rate would have to be about 2×10^5 kg s^{-1} (that is, 6×10^9 tonnes/yr). Space processing of the lunar soil would also be possible, giving $\sim 20\%$ of useful metals (Fe, Al, Ti – Ref. 5). Now the present world demand for metals is about 10^9 tonnes/yr [6], so this quantity of lunar soil should simultaneously satisfy the world demand for energy and for metals.

The costs of such a system could be < 1 m\$ kg^{-1} for mining operations (gathering up lunar soil) and ~ 10 \$kW^{-1} for the ORSs and PTS (Section 2.1) amortised over ten years, say, giving electrcity at the foot of the ladders at ~ 0.2 m\$/kWhr.

As for the used-up soil, it could be used in all sorts of landfill applications, for example, to build up the Netherlands to sea level in a century or so. One need not worry about using up the Moon, though; there is enough of it to last 10^{10} years (at the rate of 6×10^9 tonnes/yr).

It will be realised that the gravitational energy of any pair of bodies, from asteroids up to binary stars, could be extracted in a similar way. In one method a separate mass-stream orbits around both bodies and extracts energy by the gravitational slingshot effect, while a third body or mass-stream carries away the orbital angular momentum. When the Solar System energy demands greatly exceeds 10^{13} W it may prove useful to dump asteroidal material into the Sun, *via* a Solar Orbital Ring System (SORS), generating $\sim 5 \times 10^4$ kWhr/kg at a presumably modest cost.

Returning to the Earth-Moon system, we can see that the ORS makes available another alternative to space-based solar power, one which also offers a source of raw materials and metals for industry.

2.3 Earth Orbit Light-sail Windmill

The pressure of light from the Sun can be used to drive a windmill. A conventional windmill is limited in speed to the speed of sound in the blade material; an ORS windmill (Fig. 5) can avoid this limitation, thereby attaining higher efficiencies of power conversion.

Let the solar flux in Earth orbit be S (Wm^{-2}) and the light pressure on a mirror held perpendicular to the Sun-Earth direction be P (Nm^{-2}). Then

$$P = 2S/c$$

Let the thrust utilisation factor of the windmill be η, where the useful thrust produced per square metre of light-sail material is ηP. Let the circling velocity of the windmill be V_w and let the areal density of the light-sails be ρ_s.

$$\text{'Power output per unit area of sail'} = 2\eta S\, V_w/c \tag{17}$$

$$\text{'Power output per unit mass of sail'} = 2\eta S\, V_w/c\rho_s \tag{18}$$

Now the centrifugal force acting on the sails must be balanced by the gravitational force on the counterweight. For zero net weight,

$$\rho_w + \rho_s (1 - V_w^2/V_o^2) = 0 \tag{19}$$

where ρ_w is the equivalent areal density of the counterweight and the orbital velocity at the radius of the windmill is

$$V_o = (GM_\oplus/R_w)^{1/2} \tag{20}$$

Hence

'Power output per unit mass of sail' =

$$\frac{2\eta S}{c\rho_s}\left(\frac{GM_\oplus}{R_w}(1+\rho_w/\rho_s)\right)^{1/2} \tag{21}$$

Let the specific cost of sail material be c_s (\$ kg^{-1}) and of the counterweight be c_w (\$ kg^{-1}). The system cost (\$ W^{-1}) is therefore

$$K = \frac{(\rho_s c_s + \rho_w c_w)}{2\eta S/c}\left(\frac{GM_\oplus}{R_w}(1+\rho_w/\rho_s)\right)^{-1/2} \tag{22}$$

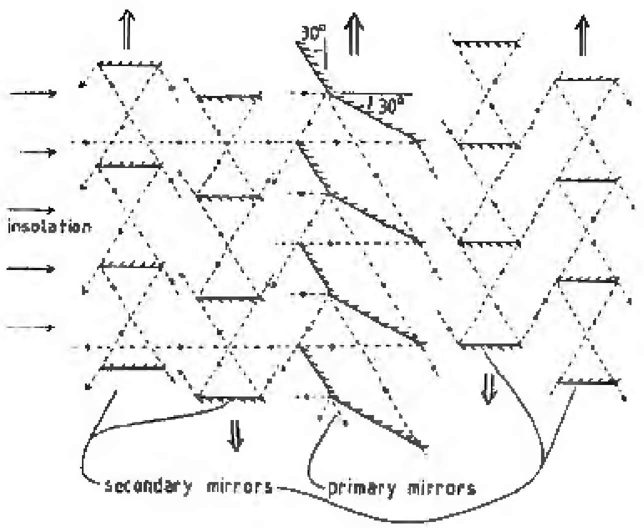

Fig. 6. A Mirror Arrangement for a Light-sail Windmill.

We can minimise this with respect to the ratio ρ_s/ρ_w and find that

$$(\rho_w/\rho_s)_{opt} = (c_s/c_w - 2) \tag{23}$$

with

$$K_{opt} = \frac{\rho_s c_w (c_s/c_w - 1)^{1/2}}{\eta S/c \; (GM/R_w)^{1/2}} \tag{24}$$

For a windmill in LEO,

$$K_{opt} \simeq 28 \, (\rho_s c_w/\eta) \, (c_s/c_w - 1)^{1/2} \tag{25}$$

As an example, consider the use of "solar-sail" material at about 6×10^{-3} kg m^{-2} and about 10 \$ kg^{-1}, using lunar soil for the counterweight at 10^{-2} \$ kg^{-1}, and a thrust utilisation of unity; this gives a generating cost $K_{opt} \simeq 50$ \$ kW^{-1}, suggesting that this is another feasible method for harnessing solar power.

Multiple mirror arrangements with counter-rotating rings can allow high values of the thrust utilisation factor, up to or exceeding unity. Figure 6 shows such an arrangement, in which the secondary mirrors have $\eta = 3/4$, the back-reflecting primaries $\eta = 3/8$ and the forward-reflecting primaries $\eta = \sqrt{3}/8$. The average value for the primary mirrors is $\eta = 3(\sqrt{3}-1)/8$. Imperfect mirrors and the finite angular size of the Sun will cause some slight degradation of η and will limit the number of mirror 'stacks' that can be used in practise.

Notice that the 30°/60° arrangement is chosen so that no light escapes through gaps, or hits the wrong side of the mirrors, even though the mirror stacks are moving past each other at high speed.

The arrangement of Fig. 7 makes use of the light twice over, so that the secondaries have $\eta = 3/2$, the forward-reflecting primaries $\eta = \sqrt{3}/4$ and the end reflectors $\eta = \sqrt{3}/2$; the stack P_2 doubles as primary and end reflector and so has $\eta = \sqrt{3}/2$. For perfect mirrors the utilisation factor of this arrangement can approach 1.5; and the thrust utilisation factor referred to the frontal area of the windmill is almost 10. In the example used above the windmill velocity is about

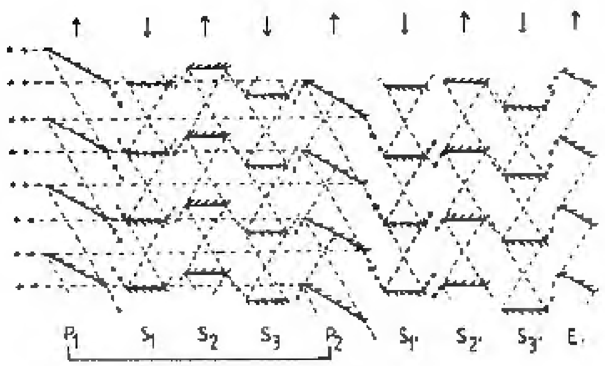

Fig. 7. A Mirror Arrangement that uses the Light twice.

240 km s^{-1} and the efficiency (power out over incident power) would be about 2.2%, which is quite high for a light-sail system. Some 10^{15} W would then be available in Earth orbit for windmills up to the height of ∿ 1000 km.

It is apparent that such light-sail windmills could be set up around other gravitating bodies also, and that the nearer the Sun they are and the higher their orbital velocity the better.

2.4 Solar Orbit Light-Sail Windmill

A slight change of geometry and we can imagine an ORS-based windmill orbiting the Sun itself. If the Sun's luminosity is $L_\odot$ and its mass $M_\odot$, then

'Power out per unit mass of sail' =

$$\frac{\eta L_\odot}{2\pi R_w^2 c_s} \left(\frac{GM_\odot}{R_w} (1+\rho_w/\rho_s) \right)^{1/2} \tag{26}$$

The system cost (\$W^{-1}) is

$$K = (\rho_s c_s + \rho_w c_w) \cdot \frac{2\pi R_w^2 c}{\eta L_\odot} \left(\frac{GM_\odot}{R_m} (1 + \rho_w/\rho_s) \right)^{-1/2} \tag{27}$$

This can be minimised with respect to the ratio ρ_w/ρ_s as in (A7.7-8), giving

$$K_{opt} = \frac{\rho_s c_w (c_s/c_w - 1)^{1/2} \cdot 4\pi R_w^{5/2} c}{\eta L_\odot (GM_\odot)^{1/2}} \tag{28}$$

It is obvious that the smaller R_w can be made the better, but heating of the light-sail will limit its nearness to the Sun. Let the absorptivity of the sail be ϵ (for light impinging upon the front surface) and let the emissivity of the back surface be near unity for the maximum allowable temperature T_m. The amount of heat absorbed per unit area, h_a, will depend slightly upon the particular mirror arrangement and upon the reflectivity of the mirrors at various angles of incidence. We put

$$h_a = \epsilon \; L_\odot/4\pi R_w^2 \tag{29}$$

By Stefan's Law the emitted heat is

$$h_e = \sigma T^4 \tag{30}$$

In equilibrium at the maximum working temperature we have

$$R_{min} = (\epsilon L_{\odot}/4\pi\sigma T_m^4)^{1/2} \tag{31}$$

The overall minimised system cost is therefore

$$K_{min} = \frac{(L_{\odot}/4\pi)^{1/4}\,(\epsilon/\sigma)^{5/4}}{(GM_{\odot})^{1/2}\,\eta\, T_m^5}\, c \cdot \rho_s c_W (c_s/c_W - 1)^{1/2} \tag{32}$$

So for a solar-orbiting windmill

$$K_{min} \simeq (0.07\ \$\ W^{-1})\, \epsilon^{5/4}\, (T_m/1000K)^{-5}\, (\rho_s c_W/\eta)(c_s/c_W - 1)^{1/2} \tag{33}$$

As an example, we use the same figures that we used above ($\rho_s = 6 \times 10^{-3}$ k gm^{-1}), $c_s = 10$ \$ kg^{-1}, $c_W = 10^{-2}$ \$ kg^{-1} & $\eta = 1$) with additional parameters applicable to aluminium ($T_m = 900K$, $\epsilon = 0.1$); we obtain $K_{min} \simeq 1.3 \times 10^{-5}$ \$W^{-1}, which compares very favourably with the Earth-orbiting windmill at the same level of light-sail technology.

The cost of a light-sail windmill in solar orbit will depend very strongly upon the maximum temperature of the mirrors, less strongly upon their reflectivity, areal density and specific cost.

Power, cheaper than any power used today (by many orders of magnitude), is available in solar orbit to a system of light-sail windmills, up to the total power output of the Sun itself.

3. FURTHER USES OF ORBITAL RING SYSTEMS

3.1 Space Platforms for Geosynchronous "Satellites"

There are many aspects of satellite communications and observations from space which would benefit from having a low altitude fixed (geosynchronous) platform from which to work, particularly if that platform is not restricted to points above the equator. A platform hung from a skyhook has the great advantage that it can be positioned far below the natural height of geosynchronous orbit; an observation "satellite" can be held stationary near to the portion of the globe it is studying and communications path lengths are greatly decreased.

Consider the range over which a skyhook is visible (Fig. 8). Now

$$C\hat{S}G = (\pi/2) - (\alpha + E) \tag{34}$$

$$\& \quad \sin C\hat{S}G/R = \sin(E + \pi/2)/(R+H) \tag{35}$$

$$\therefore \quad \alpha = \cos^{-1}(\cos E/(1+H/R) - E \tag{36}$$

Hence

$$\mathrm{arc}\,S'G = R(\cos^{-1}(\cos E/(1+H/R)) - ER) \tag{37}$$

&

$$SG = R((H/R)^2 + 2(H/R) + 2\sin E - ((H/R)^2 + 2(H/R) + \sin^2 E)^{1/2}))^{1/2} \tag{38}$$

Table 2 gives some typical values for these distances at several elevations. A skyhook (H = 300 km, say) is visible over a radius of 1500 km (at an elevation down to 4.2°) and so the skyhooks on a single ORS can offer coverage over a band nearly 300 km across. Seven polar orbital ring systems would give a global coverage. (c.f. ¾ complete coverage from three satellites in geosynchronous orbit).

The line of sight distance to a skyhook (∿ 1500 km) compares favourably with the distance to a geosynchronous satellite (∿ 40,000 km). Considering the free-space path loss for electromagnetic radiation (inverse square law) we have

$$\frac{\text{Gain of skyhook over}}{\text{geosynchronous orbit}} = \begin{matrix} 28.5\ \text{db} \\ 41.5\ \text{db} \end{matrix} \quad \text{for} \quad \begin{matrix} E = 4° \\ E = 90° \end{matrix} \tag{39}$$

The use of space platforms in communications and broadcasting has the following advantages. The down-link aerials are cheap in comparison with those of geosynchronous satellites (they need much less gain). The link-up ERP (Effective Radiated Power) is reduced by the same gain factor; hence much smaller power amplifiers and aerials can be used. It is easy to irradiate localised regions (e.g./ counties, states or countries) with different programmes; this feature is likely to be important for business data-links and in military applications. Infra-red lasers could be used for very wide bandwidth links.

In navigation, space platforms could provide fixed beacons and transponders. Space-based direction finding equipment of many kinds could be used to pinpoint shipping and air traffic and to maintain a continuous watch over each vessel and aircraft. Repeaters on the distress bands could ensure prompt response to SOS and Mayday calls.

Earth resources and meteorological satellites can conveniently be resited in space platforms: with a stable base at a low altitude, high resolution and high sensitivity mapping becomes much easier. The same applies to various forms of 'spy' satellite and remote sensing.

Thus space platforms hanging from skyhooks can have a three-fold advantage over geosynchronous satellites; they are low (or near), they are fixed (no orbital perturbations) and they can be positioned above any part of the globe.

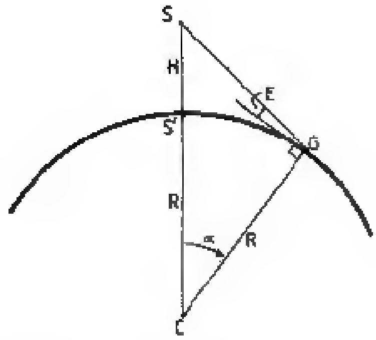

Fig. 8. Visible Range of a Skyhook.

TABLE 2. Visible Ranges of Skyhooks.

H (1) km	E (2)	SG (3) km	arc S'S (4) km
600	0°	2830	2670
	10°	1930	1760
300	0°	1980	1920
	10°	1160	1100

Notes: (1) Skyhook height; (2) Elevation of skyhook; (3) Slant range; (4) Range on Earth's surface.

Communications can also be helped by using the ladders to carry optical fibres, which may be connected through to lasers for skyhook to skyhook and deep-space links.

3.2 Space Platforms for Extraterrestrial Activities

A space platform, which is fixed relative to the Earth's surface, on which the acceleration due to gravity is about 9 ms^{-2} and which is above the atmosphere can be used in various extraterrestrial activities.

Industrial processes which need normal gravity but a hard vacuum could use such a platform; however most of these would best be carried out in an orbital SMF, portions of which can be spun to simulate gravity.

Certain scientific observations and experiments could be made in a space platform; for example, a study of the ionosphere. However, a space colony would be a better base for most deep-space observations; large instruments are cheapest in "zero-gee."

A space-port complex could be situated on a space platform. Passengers would ascend the ladder in elevators (one stream going up, another coming down) and transfer into the pressurised hotel; this would contain accommodation, restaurants and shops, as well as space-line offices and a flight-control centre. A passenger could book on an outboard flight and embark along a docking tube or gangway in a 'shirt-sleeve' environment. The ship would be lifted up on to orbital rings and would move off according to its flight plan.

Space platforms, intermediate in size between communications platforms and the ORS supported planets of Section 3.4, might be configured as habitats or employed in many ways; for example a farming platform above the North or South Pole would be good practise one day for building a planet around Jupiter.

3.3 System Expansion and Wider Scale Uses

Adding new skyhooks is simple; just 'run-up' the velocity of the rings to allow for the extra weight. The presence of additional skyhooks will make the orbit of the rings smoother and more circular.

More ORSs can be built at any attitude; they can be entirely separate or can be linked by riders. It is also possible to deploy additional orbital rings vertically above the first, and then to extend existing ladders upwards; each section of the ladders can have a high payload fraction, but the overall length and the final height can be greatly increased. Ten levels of rings can reach to the height of geosynchronous orbit.

High orbits can be reached more easily by using an Eccentric Orbital Ring System. An EORS, or a series of EORSs, can reach out to any distance from the central body. An ORS could be built to orbit both Earth and Moon together, and could be used to provide a direct link between them (the journey time at 1 g is only four hours), although this would not yet be economically worth while.

In the 'blue-skies department' there are many possible schemes in which Orbital Ring Systems can play a part. We might consider expediting interplanetary travel by building ORSs around the Sun to the radii of the planetary orbits; the same principles would apply, whether the rings were continuous cables or mass-streams composed of discrete bodies. Closely related are propulsion schemes using momentum transfer from streams of pellets aimed at spaceships (in an ORS scheme the method would be conservative of pellets and energy). Travel throughout the Solar System and beyond at a continuous 1 g acceleration would be feasible using such methods, even interstellar travel. Solar-orbiting light-sail

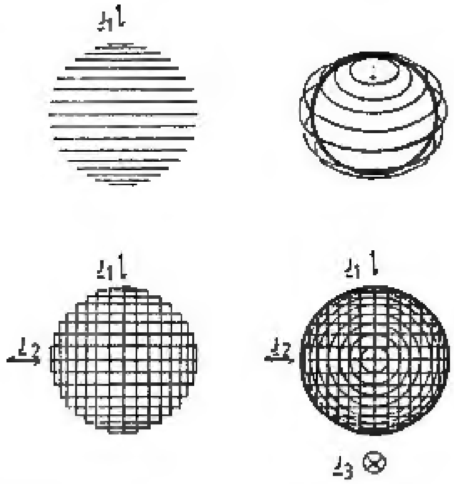

Fig. 9. A Sphere supported by Orbital Ring Systems.

windmills are considered in Section 2; a defensive weapon, the 'sunbeam,' could be developed from them, by using high-speed forward-facing mirrors to blue-shift and Döppler-beam the sunlight. Super-jovian and super-stellar planets are considered in the next section, as examples of how really enormous construction projects might be carried out using Orbital Ring Systems.

3.4 Spheres Supported by ORS

A sphere around a gravitating body can be supported by Orbital Ring Systems. The geometry of Fig. 9 avoids the problem of threading one ring over another ('ball of string problem'). The first layer of Rings is made with angular momentum vectors aligned along one axis (the x-axis, say); only the equatorial rings will be stable as drawn, the others need holding outwards. The second layer has angular momentum vectors at right-angles to the first (along the y-axis, say), and the third layer along the remaining axis (the z-axis).

At any point on the mesh the rings are capable of supporting each other and a geostationary weight. The mesh can be close, supporting a complete hollow sphere (such as an artificial planet or Dyson's sphere), or sparse; the minimum mesh has three pairs of counter-rotating rings on orthogonal axes.

3.4.1 Super-Jovian Planets

Gas giant planets need not remain forever unihabitable; a terrestrial "planet" could be built around them, supported by a tri-layer ORS mesh (Fig. 10).

The "planet" can be constructed at such a radius from the gas giant that the surface gravity is 1 g (9.81 ms^{-2}). It can be rotated upon its ORS mesh to provide day and night; it can be given mountains, seas and an atmopshere. Enormous but flimsy mirrors can be set far out in space to provide sunlight at a suitable intensity and can be used to control the weather and seasonal variations. The surface area of a super-jovian planet would be $M_{GG}/M_{\oplus}$ times that of the Earth (where M_{GG} is the mass of the gas-giant, and $M_{\oplus}$ the mass of the Earth).

For Jupiter the planetary radius would be $\approx 1.12 \times 10^8$ m (1.6 R_J) and the surface area 310 times Earth's. Configured as an Earth-like planet, with an atmospheric pressure of 10^5 Nm^{-2} and the equivalent of 40 m thickness of solid rock,

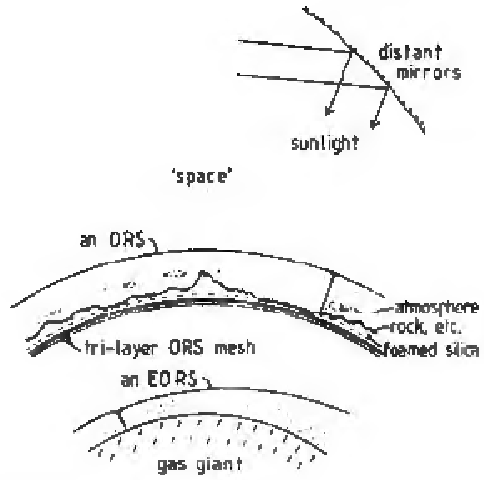

Fig. 10. A Super-Jovian Planet.

it would have an areal density $\approx 10^5$ kg m^{-2} to a total mass $\sim 2 \times 10^{22}$ kg; this amount of material is readily obtainable from the jovian satellites. Saturn, Uranus and Neptune would provide 95, 15 and 17 times the Earth's surface area respectively; gas giants in other solar systems could also be usefully 'terraformed' in this way.

It would not be necessary to build a super-jovian planet all at once. Rather, an equatorial ring or strip, perhaps less than a kilometre wide, could be built first, with walls and roof to contain the atmosphere; this could be extended gradually as required, with other strips added to fill in the mesh until the planet is complete.

3. 4. 2 Super-Stellar Planets

The concept of super-jovian planets, which surround gas-giants, can obviously be extended to super-stellar planets, which surround stars. Such a planet, supported by Orbital Ring Systems above a sun, would be a convenient form of 'Dyson's sphere' and would intercept the whole of the sun's radiation.

For an internal gravity of 9.81 ms^{-2} the radius of the sphere would be $\approx 3.7 \times 10^9$ m (5.3 $R_\odot$) for a star of solar mass. Sunlight would be distributed through ducts from the inner surface to the habitats; there would be enough to provide 100 Wm^{-2} mean insolation over as much as 4×10^{24} m^2, which is about 10^{10} times the Earth's surface area. A single super-stellar planet would have a much smaller area than this, but many such planets could be constructed in concentric layers (about 2×10^4 of them). If each layer were separated by, say, 10 km, the outer radius of the Dyson's sphere would be only about 5% more than the inner, and the surface gravity would be down by only 10%.

Such a Dyson's sphere might use active cooling and radiate waste heat from their outer surface at about 2500 K. A more efficient system would radiate from a dust shell several astronomical units in radius, at about 250 K. The dust could be charged and entrained in a magnetic field so as to flow between the layers of the super-stellar planets and out in a wide loop along the field lines; each layer would radiate to the dust at 300 K, and $\sim$ 1 tonne of dust would be needed per square meter of habitat (considerably less than the habitat mass).

Again, a complete Dyson's sphere need not be built all at once; the builders might well be content with a single super-stellar planet (only a million times the Earth's land area!) or with a sphere only partially covered by a few orthogonal strips. The construction of a narrow strip habitat could be combined with the construction of a solar light-sail windmill for electrical power; and eccentric orbital ring systems could be used for transport to other parts of the Solar System.

Almost any large body could be put to use as the central body for an ORS-supported planet, whether a gas-giant, a sub-dwarf star, a normal star, a neutron star, or even a black hole. The habitable area of the Universe could be as much as 10^{32} times that of the Earth!

4. CONCLUDING REMARKS

In Part I of this study I examined the theoretical principles of Orbital Ring Systems and Jacob's Ladders: I found that a large family of possible types exist. In Part II I examined aspects of their construction, deployment and use; I found that Orbital Ring Systems could apparently be built with present-day technology and deliver great economic benefits, reducing the likely cost of space flight by orders of magnitude; and I found them to be safe and convenient. In Part III (this paper) I have examined the contribution that systems designed around the ORSs could make to the supply of energy on Earth and in Space; I have also outlined a number of 'blue-skies' applications illustrating the potential of these concepts for the future.

An opinion that is now much in vogue is that industrial growth must stop, that resources are limited, and that conservation and redistribution of wealth should be the order of the day. This view, I believe, is wrong. It ignores the immensity and diversity of the Universe, the generosity of God, and the ingeniousness of Man.

Where there are pioneers, there will be progress; where there are barriers, they will be broken; where there is a frontier land, it will be tamed. Space is the 'High Frontier,' the great challenge to our age. If we accept this challenge we shall find adventure in exploring space, fulfilment in subduing it, and abundant wealth to wrest from it. There is a wide land there, a boundless territory; let us go forth, then, and take it, go forth and live in it.

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